Nutr Cycl Agroecosyst (2010) 87:103–114
DOI 10.1007/s10705-009-9316-1

RESEARCH ARTICLE

Nitrogen and carbon losses from dung storage in urban gardens of Niamey, Niger

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Received: 14 June 2009 / Accepted: 2 September 2009 / Published online: 19 September 2009

Abstract Intensive vegetable production in urban and peri-urban agriculture (UPA) of West African cities is characterized by high nutrient inputs. However, little is known about nitrogen (N) and carbon (C) losses in these systems, in particular during the storage of manure, the main organic fertilizer in these systems. We therefore aimed at quantifying gaseous emissions of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4) as well as leaching losses of C, N, phosphorus (P) and potassium (K) from animal manure stored in vegetable gardens of Niamey, Niger. During a first 3.5-month experiment in the hot dry season, cumulative gaseous N losses, measured with a closed-chamber system, were with 0.11 g kg^{-1} manure DM highest ($P < 0.05$) in the uncovered control treatment accounting for 1.8% of total manure N. Nitrogen losses decreased by 72% under plastic sheet roofing and by 50% under roofing + ground rock phosphate (RP) application at 333 g kg^{-1} manure DM. Carbon losses from manure amounted to 73 g kg^{-1} DM in the control and to 92 g kg^{-1} DM and 68 g kg^{-1} DM under roofing and under roofing + RP, respectively. In a second 3.5-month experiment conducted in the rainy season, C losses from the control were 164 g kg^{-1} manure DM and reduced to 77 and 65% of the control by roofing and roofing + RP, respectively. Leaching losses during the rainy season were only observed for the unroofed control and averaged 2.1 g C, 0.05 g N, 0.07 g P and 1.8 g K kg^{-1} manure DM.

Keywords Africa · Gaseous emissions · Nutrient leaching · Rock phosphate · Ruminant manure · Urban agriculture

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Introduction

From 1930–1990 the urban population in West Africa has grown by an annual rate of 4% and by 2020 63% of the total population of West Africa is expected to live in towns (Drechsel et al. 2005). Concomitantly the role of agricultural production within and at the periphery of urban areas has been rapidly rising as it provides food and employment for the urban population. Recent studies have shown that UPA supplies 10–90% of fresh vegetables, up to 70% of meat and up to 100% of eggs on city markets (Maxwell 1995; Madaleno 2000; Cofie et al. 2003; Drechsel et al. 2005). The proportion of urban households involved in UPA varies from 10 to 57% (Ellis and Sumberg 1998; Howorth et al. 2001; Asomani-Boateng 2002; Cofie et al. 2003) and so does production intensity and resource use efficiency. Sometimes, high levels of inputs used in the vicinity of human settlements have been reported to cause serious problems to human health and the environment (Ezedinma and Chukuezi 1999; Howorth et al. 2001; Asomani-Boateng 2002; Matagi 2002; Binns et al. 2003; Bryld 2003; Cofie et al. 2003; Drechsel et al. 2005).

Unless used otherwise, animal dung produced in UPA animal husbandry is an important source of nutrients and C for urban farmers (Graefe et al. 2008); however, a recent report from sub-Saharan Africa shows that manure use in UPA gardening is accompanied by substantial gaseous and leaching losses of N (Predotova et al. 2010). According to FAO-IFA (2001) the total nutrient application to African crops and grasslands contributes 12, 9 and 3% to the global emissions of N_2O-N, NO-N and NH_3-N, respectively. Proper dung handling may strongly decrease the environmental pollution and improve the nutrient use efficiency at the farm level.

Within the context of a larger effort to increase resource use efficiency in UPA, this study was conducted to quantify gaseous emissions of C and N as well as leaching loses of C, N, P and K from dung heaps in market-oriented gardening systems of a typical Sahelian town and to experimentally test approaches that could decrease such losses.

Materials and methods

Experimental setup

The dung storage experiment was conducted in *Goudel*, an inner-city quarter of Niamey (13.5°N, 2.1°E, 223 m a.s.l.), capital city of the Republic of Niger. The local southern Sahelian climate is semi-arid, with an average annual precipitation of 400–600 mm distributed unimodally from June to September; the 30-year average annual rainfall is 542 mm. Daily average temperatures peak at 34°C in May and drop to 25°C in December (World Climate 2008).

The experiment consisted of two periods of 3.5-month duration each. The first period started with the heaping of dung in the hot dry season (beginning of April 2007), the second dung heaping started at the onset of the rainy season (mid-July 2007). In both periods, 12 dung heaps of 70 kg fresh mass (30 kg DM), consisting of a 1.8:1 w:w mixture of fresh dung from cattle and small ruminants, were subjected to the following treatments: (1) heaps without any cover (treatment C, that is farmer's control with full exposure to sun and rain); (2) heaps shaded and protected from rain by a roof made from a double plastic sheet and mounted on four 0.7 m high posts (treatment R); and (3) manure homogeneously mixed with finely ground Tahoua RP (10.3% P at 19.3% solubility in citric acid and 34% solubility in formic acid; Truong et al. 1978; McClellan and Notholt 1986; van Straaten 2002) at a rate of 333 g rock powder kg^{-1} manure DM and roofed as in (2) (treatment RP). All heaps had a base area of 1 m^2 and were about 0.5 m high. Each heap was placed on an individual 1 m^2 iron sheet which had a slope of about 2% to facilitate rainfall-induced run-off during the rainy season. The sheet ended in a gutter from where run-off liquid was drained through a 2 mm mesh into a 2 l collecting container which contained 5 ml of 0.1 M HCl to minimize N volatilization. The three treatments were arranged in a completely randomized design with four replications per treatment.

Measurements of nutrient losses

Gaseous C and N emissions from the manure heaps and dung decomposition were determined 7 times during each 3.5 months period, namely at the first 2 days of weeks 1, 2, 4, 6, 9, 12, and 15, while the run-off was assessed whenever it occurred after a rainfall event.

To determine flux rates of ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) and methane (CH_4), a closed chamber system composed of a photo-acoustic infrared multi-gas monitor (INNOVA 1312-5, LumaSense Technologies A/S, Ballerup, Denmark; Kauppinen et al. 2004; Zhang et al. 2005) connected by two 0.5 m long Teflon® inflow and outflow tubes to a PVC cuvette with a diameter of 0.3 m and height 0.11 m was used (Predotova et al. 2010). To minimize adhesion of gas molecules to the surface, the inside of the cuvette was coated by a self-adhesive 0.5 mm Teflon® film (Chemfab Germany GmbH, Cologne, Germany). To ensure tight connection with the measured dung surface, the cuvette was fitted to a 0.3 m wide and 0.06 m high ring which was firmly pressed about 0.05 m deep into the dung heap.

The multi-gas monitor was manufacturer-calibrated and set to compensate cross-interferences of gases and water vapor with NH_3, N_2O, CO_2 and CH_4. A sample integration time of 5 s for each gas was chosen for which the lower detection limits were 200 μg kg^{-1} for NH_3, 30 μg kg^{-1} for N_2O, 3.4 mg kg^{-1} for CO_2 and 400 μg kg^{-1} for CH_4. Inside the cuvette the air humidity and temperature was measured with a thermo-hygrometer (PCE-313 A, Paper-Consult Engineering Group, Meschede, Germany) and the ambient air temperature and humidity was recorded during measurement periods by a HOBO Pro data logger (Model H08-032-08, Onset Corp., Bourne, MA, USA) at 1 min intervals. Each measurement time lasted for two consecutive days for which flux rates were recorded during the coldest (6–8 a.m.) and hottest (1–3 p.m.) part of the day. Measurements were taken once per heap by reading flux rates during a 1 min accumulation period taken during 5 min on the top of the heap.

Validation measurements with defined pure gases and gas mixtures conducted after the experiment at Staatliche Umweltbetriebsgesellschaft of Saxony (Radebeul, Germany) showed errors for NH_3, N_2O, CO_2 and CH_4 of −13, −12, 5 and −2% respectively, resulting in a possible underestimation of N losses and a slight overestimation of C losses with our setup.

To determine dung decomposition rates, litter bags made from nylon fibre with a mesh size of 0.2 mm were filled with 50 g (fresh weight, corresponding to about 21.4 g dry matter, DM) of dung, numbered, attached to a string and inserted into the dung heap. On Day 1 of each gas measurement period, one bag from each heap was pulled out, homogenized and frozen (−18°C) until analysis of DM, organic matter (OM) and N. Dry matter was analyzed by drying the samples at 105°C for at least 6.5 h, OM by burning at 550°C for 8 h and N was measured colorimetrically by the salicylate/nitroprusside method (Houba et al. 1995).

The amount of leached liquids was determined immediately after each rainfall by emptying the collection container into a graded volumetric flask. A sample of 100 ml of the drained liquid was collected into 150 ml flasks and stored frozen (18°C) until analysis of N, P, K as described by Houba et al. (1995) and of Corg according to Walkley and Black (van Reeuwijk 1993).

Data analysis

Flux rates of NH_3, N_2O, CO_2 and CH_4 missions were calculated by subtracting the gas concentration at the beginning of the accumulation period from the concentration at the end of the accumulation period and dividing the result by the time elapsed during the interval. Small negative emission rates which occasionally occurred during the morning measurements in the second half of each 3.5-month experiment were set to zero (Predotova et al. 2010). To estimate cumulative losses, a sinusoidal distribution of the gaseous emissions was assumed with the highest and lowest fluxes during the hottest and coldest part of the day. To approximate this, the results of the morning and afternoon measurements were averaged for each replicate separately across the 2 day measurement interval and multiplied by the time span to the next measurement period.

F-statistics to compare treatment effects on gas emission rates over time were carried out with SPSS 11.5 (Backhaus et al. 2003). To facilitate data interpretation, none of the datasets was transformed even if slight deviations from normal distribution of residuals occurred in some datasets; *F*-values are thus only approximate.

To collect information about UPA farmers' practices of dung management, the experiment was accompanied by structured interviews conducted with 215 farmers located in different quarters of Niamey.

Results

Seasonal and treatment effects on gaseous emissions

During the hot dry season, the average ambient air temperature at the experimental site was 34°C with a maximum of 45°C and a minimum of 21°C. During the rainy season, the temperature averaged 30°C (range: 20–39°C). The rainfall in 2007 amounted to

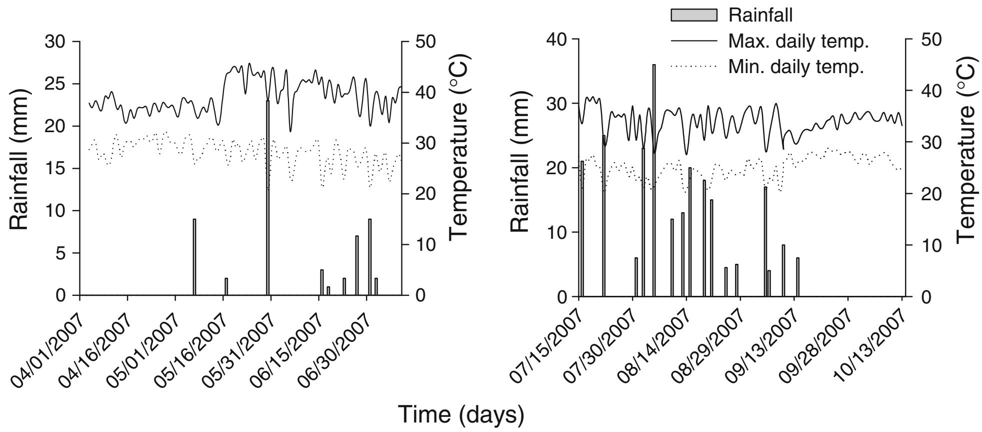

Fig. 1 Daily maximal and minimal temperatures (°C) and rainfall (mm) during the hot dry (*left*) and rainy (*right*) season in 2007 in the Goudel quarter in Niamey, Niger

371 mm (Fig. 1) of which 25% unexpectedly occurred during the first period of the dung storage experiment, with one intensive rain event at the end of May yielding 23 mm.

During the hot dry season the major form of gaseous N emissions was NH_3 of which 49–82% occurred during the evening the experiment was installed and during the first week of dung storage. Volatilization losses were highest in the R and C treatments and occurred especially during afternoons with their high temperatures (Fig. 2). Similarly to NH_3-N, the major portion of the N_2O-N losses occurred during the same evening the experiment was installed and the following morning. Fluxes of CO_2-C and CH_4-C, in contrast, did not differ much between morning and afternoon hours, but the decrease of emission rates over the duration of the experiment was as fast as for N. During the hot dry season between 31 and 43% of CO_2-C and 16–21% of CH_4-C were lost during the first experimental week.

During the rainy season, N losses as NH_3 and N_2O peaked immediately after the installation of the experiment. From the second week onwards flux rates were below 0.7 and 0.3 mg m^{-2} h^{-1}, respectively (Fig. 3). During the first experimental week CO_2-C losses amounted to 13–28% of total C losses; they were substantially higher during the hot dry than during the rainy season. After an initial peak CH_4-C emissions decreased slowly over the course of the experiment. Methane losses from control heaps (C) were much higher ($P < 0.05$) than for the two other treatments during weeks 1, 4 and 6.

For treatments R and C, total NH_3-N losses during the hot dry season were significantly higher ($P < 0.05$) than during the rainy season (Fig. 4). In the hot dry season, roofing in combination with the addition of RP led to large decreases in NH_3-N losses as compared to the two other treatments. Total N_2O-N emissions were similar in both seasons and amounted to 19, 18 and 28% of the total N losses in treatments C, R and RP, respectively. Across all treatments CO_2-C emissions were significantly higher ($P < 0.05$) in the rainy season than in the hot dry season, reaching cumulative values of 3.8 kg CO_2-C m^{-2} 106 $days^{-1}$, 3.2 kg CO_2-C m^{-2} 106 $days^{-1}$ and 4.9 kg CO_2-C m^{-2} 106 $days^{-1}$ for treatments R, RP and C, respectively. Cumulative CH_4-C losses were with 27.2 g CH_4-C m^{-2} 106 $days^{-1}$ twice as high for the untreated control as for R and RP in the rainy season (Fig. 4).

Treatment effects on leaching losses and manure decomposition

Leaching losses occurred only after rainfall events in the unroofed control heaps, which were exposed to the rain. As some unexpected rainfall occurred at the end of the hot dry season, some leaching losses were also recorded in the first period of the experiment. However, cumulative leaching losses were much higher during the rainy than during the hot dry season (Fig. 5).

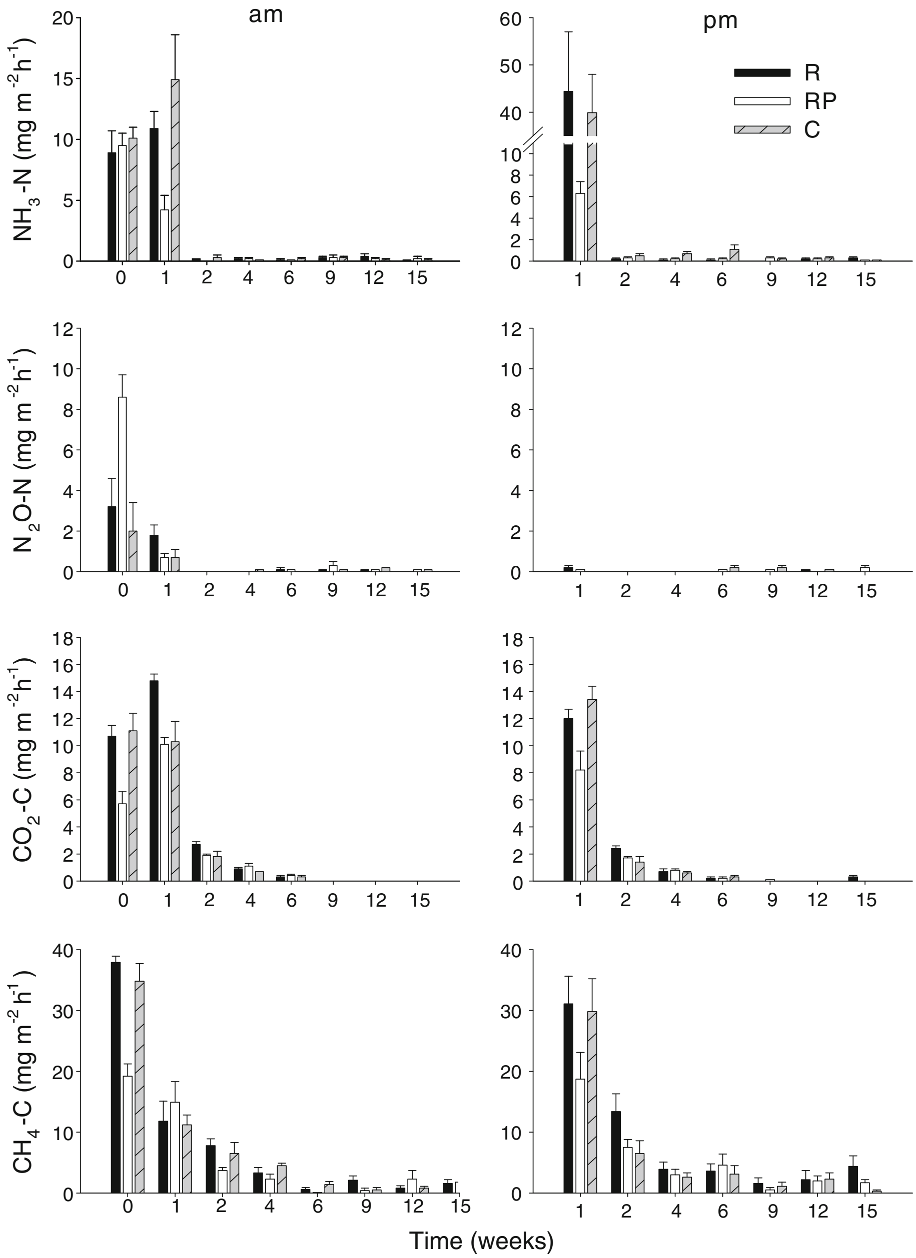

Fig. 2 Gaseous emissions of three dung storage treatments during the hot dry season 2007, Niamey, Niger. Means ($n = 8$) and standard errors from 1st to 15th week ($n = 4$ for time zero). The *bars* at time zero illustrate the emissions immediately after installation of the dung heaps in the late evening when ambient air temperatures were more similar to morning than to midday conditions

The DM content of the manure fresh matter inside the nylon bags increased during the hot dry season (Fig. 6) from an initial 378 g kg^{-1} (R), 470 g kg^{-1} (RP) and 375 g kg^{-1} (C), to 825 g kg^{-1}, 752 g kg^{-1} and 838 g kg^{-1}, respectively. For treatments R and RP, the drying of the dung heaps was much slower during the rainy season than during the hot dry season. Overall OM decomposition was slow and slightly reduced by RP application (Fig. 6). For all treatments, the C/N ratio (Fig. 7) of the dung ranged

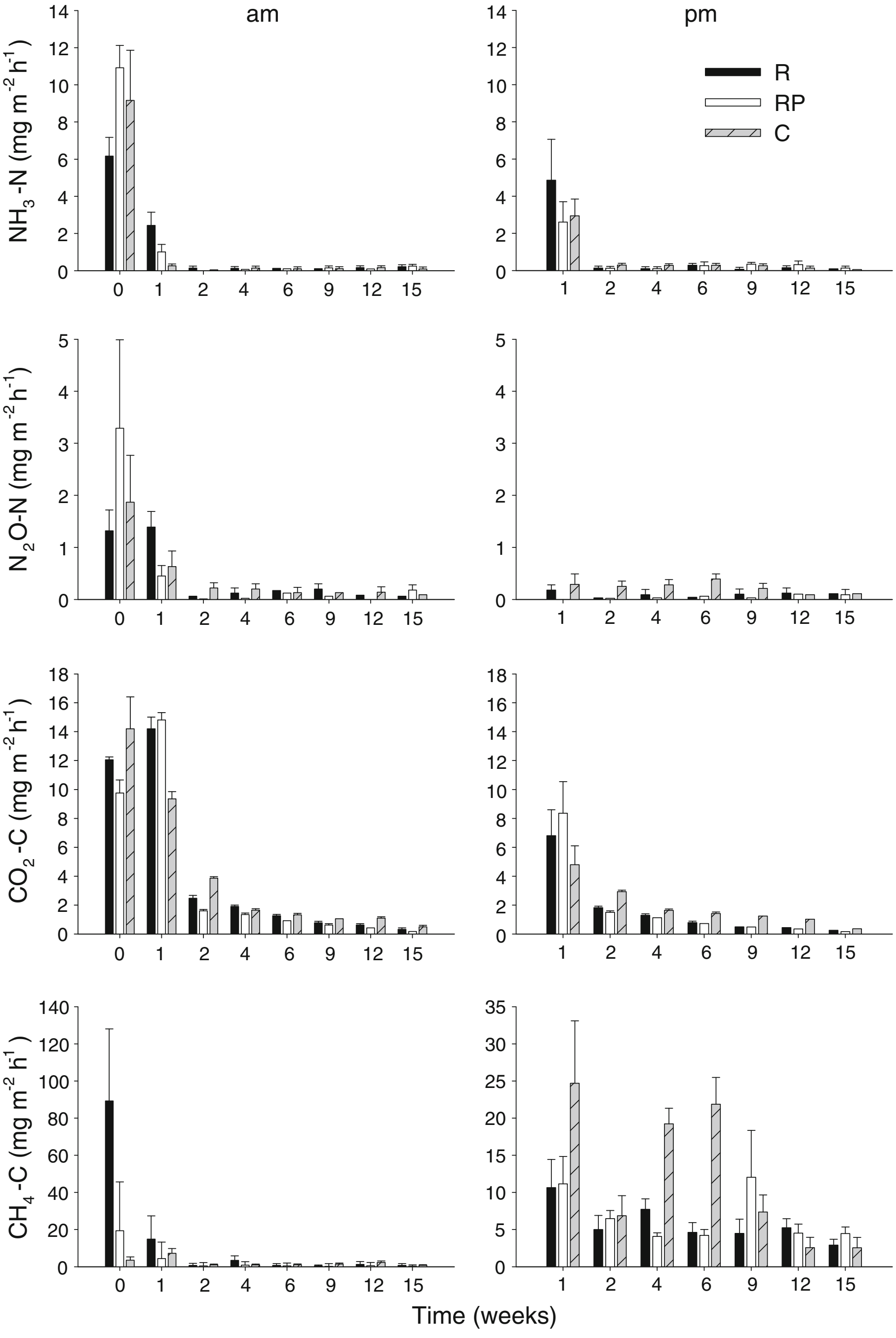

Fig. 3 Gaseous emissions of three dung storage treatments during the rainy season 2007, Niamey, Niger. Means ($n = 8$) and standard errors from 1st to 15th week ($n = 4$ for time zero). The *vertical bars* at time zero illustrate the emissions immediately after installation of the dung heaps in the late evening when ambient air temperatures were more similar to morning than to midday conditions

between 23 and 27 during the hot dry season; the only exception being the initial C/N ratio determined for dung mixed with RP. During the 3.5 months of rainy season experimentation, the C/N ratio decreased from 30 to 21 in treatment R, from 34 to 24 in treatment RP and from 28–23 in treatment C.

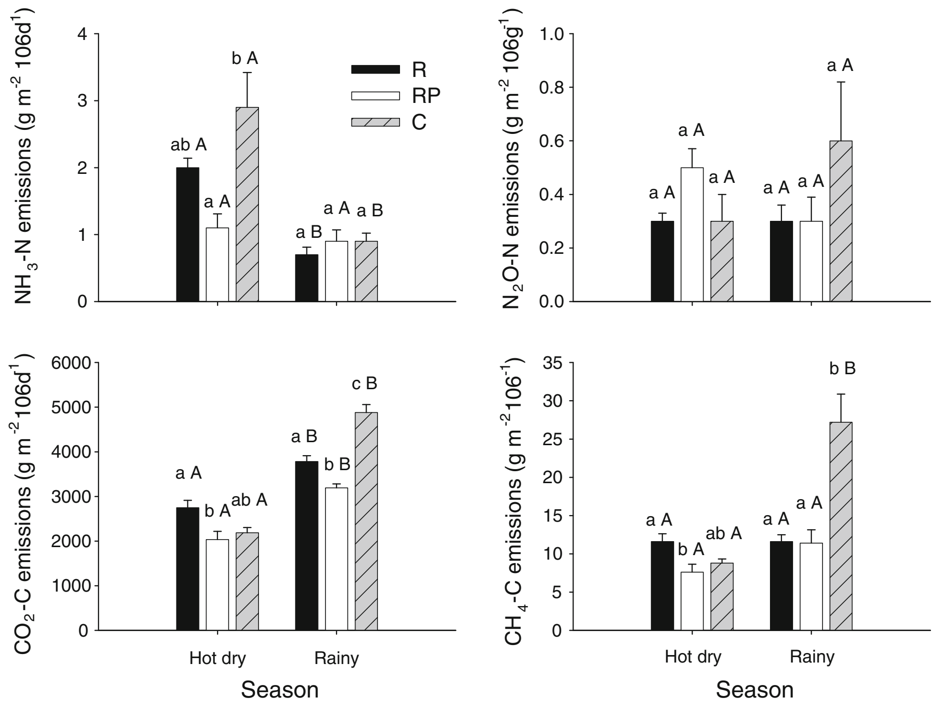

Fig. 4 Total N and C losses as NH_3, N_2O and CO_2, CH_4, respectively, from a dung storage experiment in Niamey (Niger) lasting for 106 days. Data show means ($n = 4$) with their standard errors. *Different small letters* indicate differences ($P < 0.05$) between treatments within one season whereas *different capital letters* indicate differences ($P < 0.05$) between seasons for each treatment

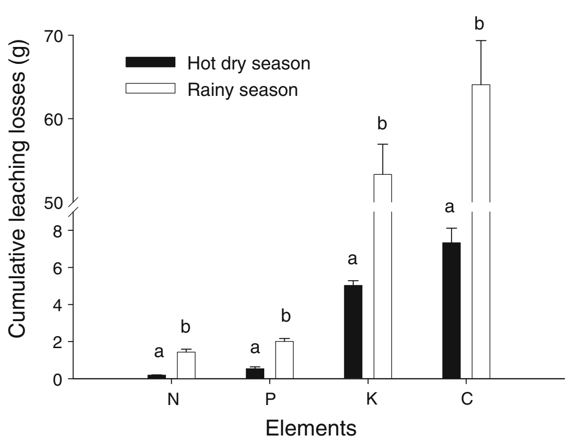

Fig. 5 Cumulative leaching losses from the control treatment of a dung storage experiment conducted in Niamey (Niger) in 2007; data show means ($n = 4$) and standard errors. *Different letters* indicate differences ($P < 0.05$) between seasons

Farmers' manure storage practices

The results of the interviews showed that most of the UPA farmers (99.5%) applied purchased or their own animal manure to their fields and gardens; 67% of the respondents applied mineral fertilizers in addition to manure. The dung was transported to the garden by animal drawn carts (13%), manually (27%), by car (25%) or by a combination of the former (35%), often every two (57%) or four (31%) weeks. Almost half of the farmers (49%) transported the dung from a distance <1 km to the garden, while about one-third (28%) fetched the dung from distances >3 km. All dung was stored in unprotected (un-roofed) heaps before application, which usually occurred within 2–3 days (69%) after the dung had been brought to the garden. In most gardens, the dung was applied to the surface of plots after hoeing (93%). The majority of farmers (97%) applied the dung during the cooler parts of the day, that is during mornings or/and evenings.

Discussion

The decrease in gaseous emissions over the duration of the experiment was slower for C than for N, with

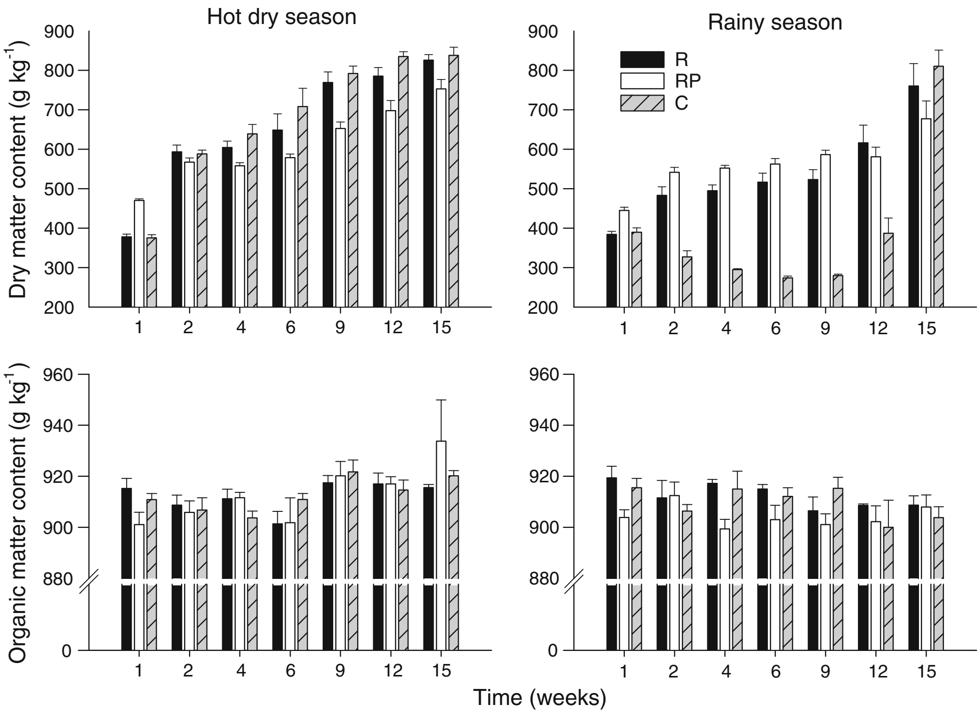

Fig. 6 Moisture and organic matter content of animal manure (dung) incubated in nylon litter bags during the hot dry and rainy season 2007 in Niamey, Niger. Data show means ($n = 4$) and one standard error of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate (RP) kg^{-1} manure DM

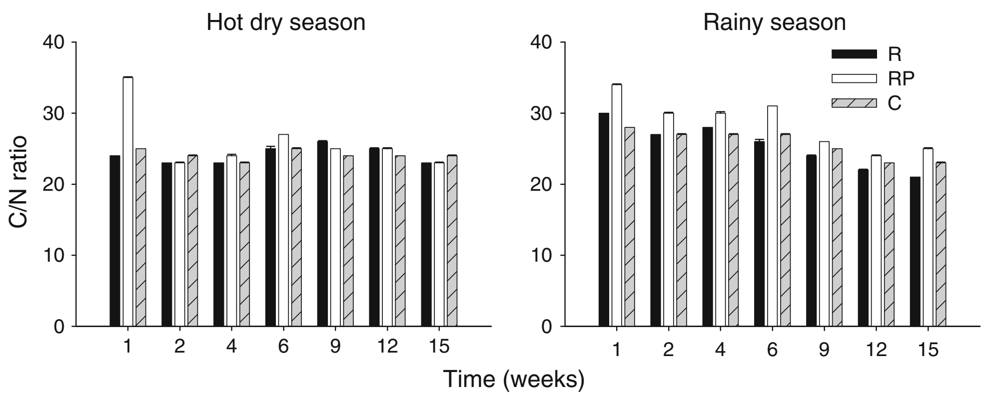

Fig. 7 C/N ratio of animal manure (dung) incubated in nylon litter bags during the hot dry and rainy season 2007 in Niamey, Niger. Data show means ($n = 4$) and one standard error of the untreated control treatment (C), dung protection by a plastic roof (R) and roof-protection combined with the addition of 333 g finely ground rock phosphate kg^{-1} manure DM (RP)

the exception of the CH_4-C efflux in the control treatment during the rainy season (Fig. 3). The surprisingly high afternoon flux rates in weeks 1, 4 and 6 in the rainy season might have been caused by concomitant rainfall events leading to temporarily anaerobic conditions in the unroofed dung heaps and favourable conditions for methane producing bacteria (Gupta et al. 2007).

Our results of high gaseous N losses immediately after dung storage on heaps confirm similar data of

Sommer (2001) and Sommer and Dahl (1999). These authors reported that during the composting of litter significant NH_3-N emissions only occurred during the first 10 days of the experiments and accounted for 1.5% of the total initial N content in the substrate. This figure is similar to the total N losses from treatments C and R in our experiments, which during the hot dry season ranged from 1.3 to 1.8% of total N in the dung heaps. Ammonia emissions were the predominant form of N losses (Rufino et al. 2006) and were responsible for 87, 69 and 91% of the total volatilized N for treatments R, RP and C, respectively. Lower storage losses of N_2O-N than of NH_3-N were also reported by Oenema et al. (2007), Külling et al. (2003) and Sommer (2001). Similarly to our observations, Hellmann et al. (1997) reported N_2O production during the first few days of their composting experiment to depend on the availability of NH_3 as a substrate for nitrification. According to Sommer (2001) and Hellmann et al. (1997), the subsequent increase of substrate temperature inhibited the nitrification and de-nitrification through thermophobic microorganisms. In contrast to their results, the N_2O-N emissions in our experiment did not increase later on and from the second experimental week onwards the temperatures in the top 0.1 m of the substrate remained between 33–40°C and 29–32°C during the hot dry and the rainy season, respectively. This might be due to the warm climatic conditions in which our experiment was conducted.

In both seasons the addition of ground RP decreased cumulative N losses to 0.1% of the total initial N stock, which may be due to N absorption by the large surfaces of the fine RP particles. Such effects of finely ground minerals on NH_3-N emissions during composting were previously reported by Zaied and Van den Weghe (2000). In contrast, RP application did only have minor effects on gaseous C fluxes which reached a total of 15–20% of the initial C content in the hot dry season and 24–36% in the rainy season. The latter losses are several-fold higher than the 10% C loss reported from a composting of diary cows deep litter during the winter months in Denmark by Sommer and Dahl (1999). This may have been due to the prolonged storage of the manure (Table 1) under more favourable conditions for ruminant dung decomposition under the hot and wet weather conditions of the Sahelian rainy season (Esse et al. 2001).

For our experiments, the mixture of manure from small ruminants and cattle as typically used by local farmers (Table 1) was brought fresh (1–2 days old) from the stables of urban livestock keepers. Large gaseous N and C losses are likely to occur immediately after manure spreading: Sommer and Hutchings (2001) reported that 50% of the total NH_3-N was volatilized during the first 24 h after application. The results of our interview show that more than half of the farmers (51%) transported the animal manure from a distance bigger than 1 km every 2 or 4 weeks (Table 1) which resulted in prolonged storage under unroofed conditions. Carbon and N losses that occurred immediately after manure deposition at the farms, during dung mixing, loading at the farm gate, transport to and storage in UPA garden areas (Hao et al. 2001; Sommer 2001) were not measured, therefore the real N and C losses along the entire manure management chain will have been much higher that estimated in our study.

The results showed that the use of a simple plastic roof effectively eliminated leaching losses of K and C during the rainy season. Sommer (2001) reported cumulative K leaching losses from cattle manure storage during 132 days to range from 8 to 16% of the initial K content which is similar to the 16% K lost in our rainy season experiment (Table 2). The high C and K leaching losses measured in our study are likely to be representative for UPA gardens in Niamey as none of the interviewed farmer used any cover to protect manure storage heaps. In most years leaching losses may even be higher as during 2007 when total rainfall was with 371 mm much lower than the annual average of 542 mm.

In SW Niger many studies have been conducted on how to alleviate the notoriously low P status of the dominant acid sandy soils (Bationo and Mokwunye 1991; Kretzschmar et al. 1991; Buerkert et al. 1998; Buerkert et al. 2001; Somado et al. 2003). While Squalli and Nadir (1983) suggested the use of soluble superphosphate for arid Moroccan market gardens, in Niamey the locally available inexpensive Tahoua RP (costs were 0.5 € per 10 kg in 2007) of which high agronomic efficiencies for on-farm millet fields were previously reported by Bationo et al. (1990), might present an effective way of increasing garden soil P stocks while decreasing N losses during dung storage.

Successful use of the closed chamber system with the photo-acoustic infrared INNOVA monitor has

Table 1 Categorized results of an interview of 215 gardeners in 6 city quarters of Niamey, Niger (2007)

Question	Category (% of total 215 gardeners)			
Nationality	Niger	Burkina Faso		
	31	69		
Ownership	Owner	Rented		
	29	71		
Cultivated area	<250 m^2	251–750 m^2	>751 m^2	
	51	45	4	
Area abandoned during hot dry season	<25%	26–50%	51–75%	>75%
	8	57	24	11
Chemical fertilizer use	No use	Urea only	NPK only	Urea + NPK
	33	8	31	27
Animal dung use (several answers possible)	Cattle	Small ruminants		
	98	87		
Dung origin	Purchased	From own animals	Both	
	69	3	28	
Frequency of dung import to the garden	Every 1 week	Every 2 weeks	Every 4 weeks	Not regularly
	9	57	31	3
Dung transport distance	<1 km	1–3 km	>3 km	
	49	23	28	
Dung transport means	Animals	People	Car	Combined
	13	27	25	35
Person responsible for the dung transport	Gardner	Children	Hired labor	Gardner + hired labor
	25	2	43	30
Duration of dung storage in garden before application	Immediate application	1 day	2–3 days	1 week
	4	26	69	1
Type of dung storage	In heaps, unprotected	Covered		
	100	0		
Dung application time	Mornings	Evenings	Mornings or evenings	Any time
	26	14	57	3
Type of dung application	On the surface	On the surface after hoeing	Incorporated into the topsoil	
	6	93	1	
Reason for using animal manure (several answers possible)	Cheap	Accessible	Good growth/harvest of crops	Own animals' supply
	32	3	98	2

been reported in earlier studies measuring gaseous emissions from a range of soils. The most critical factor determining the reliability of the method in hot environmental conditions seems to be the length of the gas accumulation period. In the literature reported accumulation periods range from 2 to 3 min (Hans et al. 2005; Reth et al. 2005) until 1 h (Velthof et al. 2003; van Groenigen et al. 2005). Because in our study the rapid increase in gas concentration, the raise in temperature and the built-up of humidity in the cuvette, especially during the midday measurements, influenced emission fluxes (feed back mechanisms), we have shortened the accumulation period to 1 min.

Table 2 Cumulative gaseous and leaching losses (in absolute terms and as a proportion of the total initial C, N, P and K content) from three different dung storage treatments ($n = 4$/treatment) during the hot dry and rainy season 2007 in Niamey, Niger

Season	Treatment	Cumulative gaseous losses				Cumulative leaching losses							
		N (g 106 days^{-1})	C	N (% of initial content)	C	C (g 106 days^{-1})	N	P	K	C (% of initial content)	N	P	K
Hot dry	Roof	2.3	2,759	1.3	20.1								
	Roof + P	1.6	2,039	0.1	15.1								
	Control	3.2	2,193	1.8	16.1	7.3	0.2	0.5	5.0	0.1	0.0	0.3	1.2
Rainy	Roof	1.0	3,793	0.7	27.5								
	Roof + P	1.2	3,201	0.1	23.6								
	Control	1.5	4,904	0.9	35.7	64.1	1.4	2.0	53.3	0.5	0.3	1.2	16.0

Conclusions

During the hot dry season a simple plastic sheet roofing and addition of ground RP to stored ruminant manure decreased total N gaseous losses by 50% in comparison to dung directly exposed to the sun. In absolute terms these N losses were rather small which was most likely due to the fact that during the transfer of the manure from the stable to the dung heap much of the easily mineralizable and mineral N has already been lost. Plastic roofing also protected dung heaps from leaching losses during the rainy season. In order to decrease N volatilization from dung heaps and simultaneously increase P stocks in garden soils, the addition of finely ground RP to dung heaps proved particularly effective.

A closer linkage between animal keepers and gardeners and increased awareness of simple and locally accessible techniques to reduce volatilization and leaching losses of C and N from manure heaps may help to increase the nutrient use efficiency in UPA gardens across the Sahel.

Acknowledgments We are indebted to Rainer Georg Joergensen for his helpful advice, to Issa Karimou, Claudia Thieme and Eva Wiegard for technical assistance, to ICRISAT Sahelian Centre and EIRENE for logistical support and to the Deutsche Forschungsgemeinschaft (DFG) for funding.

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